The Astrophysical Journal, 226:L39–L42, 1978 November 15

MOLECULAR CLOUDS IN THE VICINITY OF W3, W4, AND W5

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Received 1978 May 23; accepted 1978 August 15

ABSTRACT

A well-sampled survey of CO emission has been made over 16 square degrees surrounding W3 (IC 1795), W4 (IC 1805), and W5 (IC 1848), a chain of bright H II regions in the Perseus arm of the Galaxy. Two massive ($\sim 10^5 M_\odot$) complexes of CO emission are found, and a detailed examination of the complex associated with the W3–W4 region has been made. We find that the most recent OB star formation has taken place nearly simultaneously within three fragments of a long ($\sim$36 pc), narrow ($\sim$6 pc) high-density layer at the edge of a large molecular complex. The outer boundary of this star-forming layer appears to be in physical contact with the extended ionization front surrounding the exciting stars of W4. Measurements of CO column density in the cloud from both within and outside the high-density layer are consistent with the hypothesis that the material in the layer has been swept up from the volume now occupied by the W4 H II region. Estimates of the effects of the available sources of Lyman-continuum luminosity and stellar winds indicate that the pressure from these sources may have played a significant role in sweeping up the observed layer during the 6×10^6 year lifetime of the W4 exciting cluster. The relatively recent onset of OB star formation within the layer provides strong observational evidence for a history of sequential, burstlike star formation in this OB association.

Subject headings: clusters: associations — interstellar: molecules — nebulae: general — stars: formation

I. INTRODUCTION

W3 (IC 1795), W4 (IC 1805), and W5 (IC 1848) are a chain of H II regions in the Perseus arm which are among the best known examples of OB star birth in our Galaxy. Several properties of the W3 and W4 regions make them uniquely suited for a detailed study of the process of such star formation. First, the orientation of this complex is highly favorable for observation, since the components (i.e., OB stars, ionization fronts, compact continuum sources, molecular clouds, maser sources, etc.) which provide the relevant data concerning the birth and early evolution of massive stars have little overlap in the line of sight. This permits better examination of the interaction between these components than is possible in otherwise comparable sources such as Orion or M8. Second, the groups of compact continuum sources [i.e., W3 and W3(OH)], located at the edge of W4, are the best-known examples of young massive stars evolved enough to be unequivocally distinguished as OB stars yet not sufficiently evolved to disrupt their molecular envelopes. In such a situation, the relatively undisturbed molecular environment of a very young star-forming region can be studied in detail. Finally, the high latitude of these sources and their intense radio brightnesses have made this one of the best-studied star-forming regions in the sky.

Although more than 20 years ago Sajn (1954) suggested that the three H II regions W3, W4, and W5 might be physically related, most infrared and radio studies of this complex have ignored its large-scale structure and primarily dealt with the intense compact H II regions associated with W3. Recently, Wendker and Altenhoff (1977) published a moderate-resolution (10′) continuum map of the entire W3–W4–W5 region, but corresponding molecular observations have been lacking. In order to properly understand the evolution of the region and the interrelationship between its various star-forming components, a detailed and large-scale mapping of the associated molecular clouds is necessary. In this *Letter* we present initial results of the first extensive and well-sampled CO map of the entire W3–W4–W5 complex; more detailed results will be reported elsewhere.

II. OBSERVATIONS

The Columbia 1.2 m Cassegrain telescope (Cohen and Thaddeus 1977) was used to completely sample CO emission from the W3–W4–W5 complex at an angular resolution of 8′. Spectra were obtained with 1 MHz (2.6 km s^{-1}) resolution, using a 40-channel filter bank. CO observations with an angular resolution of 2.′3 were obtained with the 5 m telescope of the University of Texas Millimeter Wave Observatory, using a 40-channel filter bank with spectral resolution of 0.25

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MHz (0.65 km s^{-1}). The ^{12}CO brightness temperatures were corrected for atmospheric and instrumental effects, following Davis and Vanden Bout (1973).

Figure 1*a* (Plate L2) summarizes the results of the Columbia observations in the form of a contour map of *integrated* ^{12}CO emission overlaid on the corresponding fields of the Palomar Sky Survey. Two large cloud complexes are within the area surveyed: one is associated with the H II region W5, and the second with the H II regions W4 and W3. The discussion in this *Letter* will focus on the second complex.

Figure 1*b* shows a map of the *peak* ^{12}CO brightness temperature for the W3–W4 region obtained with the 5 m telescope. Three bright (i.e., $T_b > 20$ K) CO condensations are resolved in this map. Table 1A lists the relevant observed properties of these objects. These three condensations (designated I, II, and III) are located within the molecular cloud along its boundary with the extended ionization front surrounding W4. CO emission abruptly decreases across this boundary, suggesting the presence of a sharp molecular dissociation front. Relatively weak CO emission extends over a much larger area to the west of the bright condensations.

The ^{13}CO observations made with the 5 m telescope were used to estimate column densities and masses for the cloud complex in the usual manner (Elmegreen and Elmegreen 1978*b*; Dickman 1975). The results are listed in Table 1B. The masses contained within the 15 K contours around each of the bright condensations is estimated to be approximately 10^4 $M_\odot$. The mass contained within the 10 K contours surrounding the three sources is estimated to be 4×10^4 $M_\odot$, while the mass of the remaining low-temperature gas to the west is about 3×10^4 $M_\odot$. Thus the total mass of the entire cloud is approximately 7×10^4 $M_\odot$, of which roughly 60% is located within the 10 K contours surrounding the three bright CO condensations. The average ^{13}CO column density is a factor of about 5 greater in this high-temperature region than it is in the remaining 80% of the projected area of the molecular cloud. Thus we refer to the area of $T_b \geq 10$ K surrounding condensations I, II, and III as the high-density layer (HDL). Sharp changes in the velocity field are observed between the HDL and the rest of the molecular cloud, suggesting distinct dynamical natures for the two objects. The velocity within the HDL also varies considerably (e.g., Table 1B). We will defer discussion of the velocity structure of this complex to our second, more detailed, paper.

TABLE 1B

COLUMN DENSITIES AND MASSES

	$N(^{13}CO) \times 10^{16}$ (cm^{-2})	$M/M_\odot$
I..................	8	1.2×10^4*
II.................	5	0.6×10^4*
III................	3	1.2×10^4*
HDL...............	3†	4.5×10^4
Rest of cloud........	≤0.5‡	$\leq3.0\times10^4$

* Derived assuming that for $T \geq 15$, $N = 5.2 \times 10^{16}$ cm^{-2}, and that the projected area of the source is same as area enclosed by 15 K contour.

† Average column density for $T^{12} \geq 10$ K.

‡ Average column density for $10 > T^{12} \geq 5$ K.

III. DISCUSSION

One of the most striking features of Figure 1*b* is the close correspondence between the ionization front of W4 and the edge of the molecular cloud. This implies that the ionization front and the molecular cloud are physically interacting. Adjacent to this ionization front there is an extended, relatively narrow high-density layer of molecular gas. A particularly interesting aspect of this layer is the clear appearance of fragmentation into three dense, hot objects. Condensations I and II are associated with W3 and W3(OH), respectively, and contain unmistakable evidence for recent OB star formation (see Mezger and Smith 1977). The third and southernmost bright source is near the far-infrared source no. 5 (FIRS 5) discovered by Fazio *et al.* (1975). The rest of the molecular cloud is apparently quiescent; CO emission is weak and there is no indication of OB star formation.

What were the events which led to the origin, fragmentation, and subsequent OB star formation in the HDL? The massive stellar objects in W3 and W3(OH) have been formed within the last 10^5 years (Mezger and Smith 1977), so the final collapse of the HDL must be very recent relative to the formation of the exciting stars of W4 some 6×10^6 years ago (Stothers 1972). The existence of such young stellar objects next to the older OB stars of W4 clearly suggests that star formation in this region has proceeded in a sequential manner. Although suggestive, this need not imply that the older stars have caused the formation of younger ones, but our observations of the molecular gas provide evidence that they have. In particular, the formation of OB stars in the HDL appears to be a direct result of the

TABLE 1A

OBSERVATIONS

Source	α(1950)	δ(1950)	$T_b(^{12}CO)$ (K)	$T_b(^{13}CO)$ (K)	$v_{LSR}{}^{13}$ (km s^{-1})	Δv^{13} (km s^{-1})
I (W3)................	02^{h}21^{m}52^s	+61°52′18″	29	5.5	−40	6.1
II [W3(OH)]..........	02 23 20	+61 38 48	24	6.6	−48	3.1
III (FIRS 5)..........	02 24 34	+61 17 48	22	5.8	−50	2.4

interaction of the older OB stars in W4 with the molecular complex.

The sequence of events following the formation of OB stars in a neutral cloud has been discussed by Kahn (1954) and recently applied to molecular clouds by Elmegreen and Lada (1977). As an ionization front advances into the molecular gas, a small amount of the neutral material becomes dissociated and ionized, while the larger part is swept up into a dense, thin shell. Could the HDL be such a shell? If the molecular gas in the HDL were to be spread uniformly from the present edge of the cloud to the position of the exciting cluster (in W4), then the resulting area of about 20×40 square parsecs would be filled with a column density of ^{13}CO of about 6×10^{15} cm^{-2}. This is nearly the average column density in the molecular cloud now ahead of the HDL (see Table 1B) and it is therefore plausible that the HDL has been swept up from an initially more uniform cloud.

To decide whether ionization fronts or stellar winds or both could have swept up this amount of matter, we consider the following simple calculation. The cluster, IC 1805, contains nine stars of spectral type O9 or earlier (Cruz-Gonzales *et al.* 1974) which have provided a continuous source of pressure from ionization fronts and possibly stellar winds over the last 6×10^6 years. Following Rubin (1968) we estimate the Lyman-continuum luminosity S from the observed radio continuum flux of W4. From the data of Wendker and Altenhoff (1977), and assuming a distance of 2 kpc, we find $S \approx 1.5 \times 10^{50}$ s^{-1} for both W4 and W3. To correct for the presence of W3, which is embedded in the molecular ridge and was not a source of pressure for the expansion of W4, we use the 15 GHz observations which isolate W3 (Schraml and Mezger 1969) to find a value of S for W3 alone of 2.8×10^{49} s^{-1}. The ionizing luminosity of W4 is taken to be the difference between these two values, or $S \approx 1.2 \times 10^{50}$ s^{-1}. The mechanical luminosity from the wind of a typical O star is $\sim 1.2 \times 10^{36}$ ergs s^{-1} (Weaver *et al.* 1977), so the total power in the wind from IC 1805 is estimated to be $L \sim 10^{37}$ ergs s^{-1}. The initial density of the ambient molecular cloud may be estimated from the ^{13}CO column density outside the HDL, 5×10^{15} cm^{-2}, by assuming that the line-of-sight depth of the cloud equals its transverse dimension of $\sim$15 pc (corresponding to $\sim 25'$ in Fig. 1*b*). Using a conversion factor $N(^{13}\mathrm{CO})/N(\mathrm{H}) \approx 1 \times 10^{-6}$ from Dickman (1975), we obtain $n(\mathrm{H}) \sim 100$ cm^{-3}.

These parameters can be used to estimate the radii of the shells that would result either from stellar winds or from the expansion of ionized gas. For stellar winds, the radius increases with time t as (Weaver *et al.* 1977)

$$27\, n_{\mathrm{H}}^{-0.2}(L/10^{36}\ \mathrm{ergs\ s^{-1}})^{0.2}(t/10^6\ \mathrm{yr})^{0.6}\ \mathrm{pc} \approx 50\ \mathrm{pc}$$

after 6×10^6 years. For an expanding H II region without a stellar wind, the radius would be (Spitzer 1968)

$$r_s\left(1 + \frac{7}{4}\frac{c_{\mathrm{II}}}{r_s}\,t\right)^{4/7} \approx 40\ \mathrm{pc}\,.$$

for $r_s = (3S/4\pi n_{\mathrm{H}}^2\alpha)^{1/3}$, $c_{\mathrm{II}} = 13$ km s^{-1}, and $\alpha = 3.1 \times 10^{-13}$ cm^3 s^{-1}.

The observed projected separations between the exciting stars in W4 and the three bright CO sources are roughly 16, 27, and 36 pc. Apparently these observations are consistent with the idea that the pressure from the expanding H II region and stellar winds around the exciting stars of W4 could have swept up the observed high-density layer at the edge of the molecular cloud.

It is conceivable that a supernova explosion in the cluster IC 1805 provided an additional source of pressure for forming the HDL. Although no direct evidence for such an explosion is available at the present time (however, see Caswell 1967), we should not overlook the possibility that a supernova remnant is now obscured by the H II region.

The inclusion of a supernova, or any other additional source of pressure (e.g., the rocket effect; Oort and Spitzer 1955), in conjunction with stellar winds and the expanding H II region would accelerate the formation and development of the HDL. Other factors, such as the orientation of the general magnetic field (Elmegreen and Lada 1977), differences in galactic gravitational potential perpendicular and parallel to the plane, and preshock density inhomogeneities, would also affect the evolution and observed appearance of the HDL. Consequently, it may be premature to attempt to explain all the details of cloud structure on the basis of a simple model. Nonetheless, it is apparently not necessary to consider these complexities or additional pressure sources in order to account for the gross properties of the HDL.

We would expect that at some point in its evolution, such a swept-up layer will become gravitationally unstable and form stars (Elmegreen and Lada 1977). The events which occur between the onset of significant gravitational instability and the first appearance of massive protostars in the layer are undoubtedly complex, and it is difficult to determine the times required for these processes. However, these times are likely to be short compared with the sweeping-up time (Elmegreen and Lada 1977; Elmegreen and Elmegreen 1978*a*). If this were not the case, it would be difficult to understand how two of the three molecular condensations in the HDL have simultaneously produced new OB stars.

One wonders whether similar swept-up star-forming layers exist in other OB associations and have escaped notice. Unfavorable line-of-sight orientations, highly inhomogeneous initial clouds, and a lack of sufficient large-scale CO observations could all contribute to the difficulty of recognizing such layers in other sources. The observations reported here indicate that an effort to detect similar layers elsewhere may be worthwhile.

We are grateful to Dr. William DeCampli for assistance with the Texas observations.

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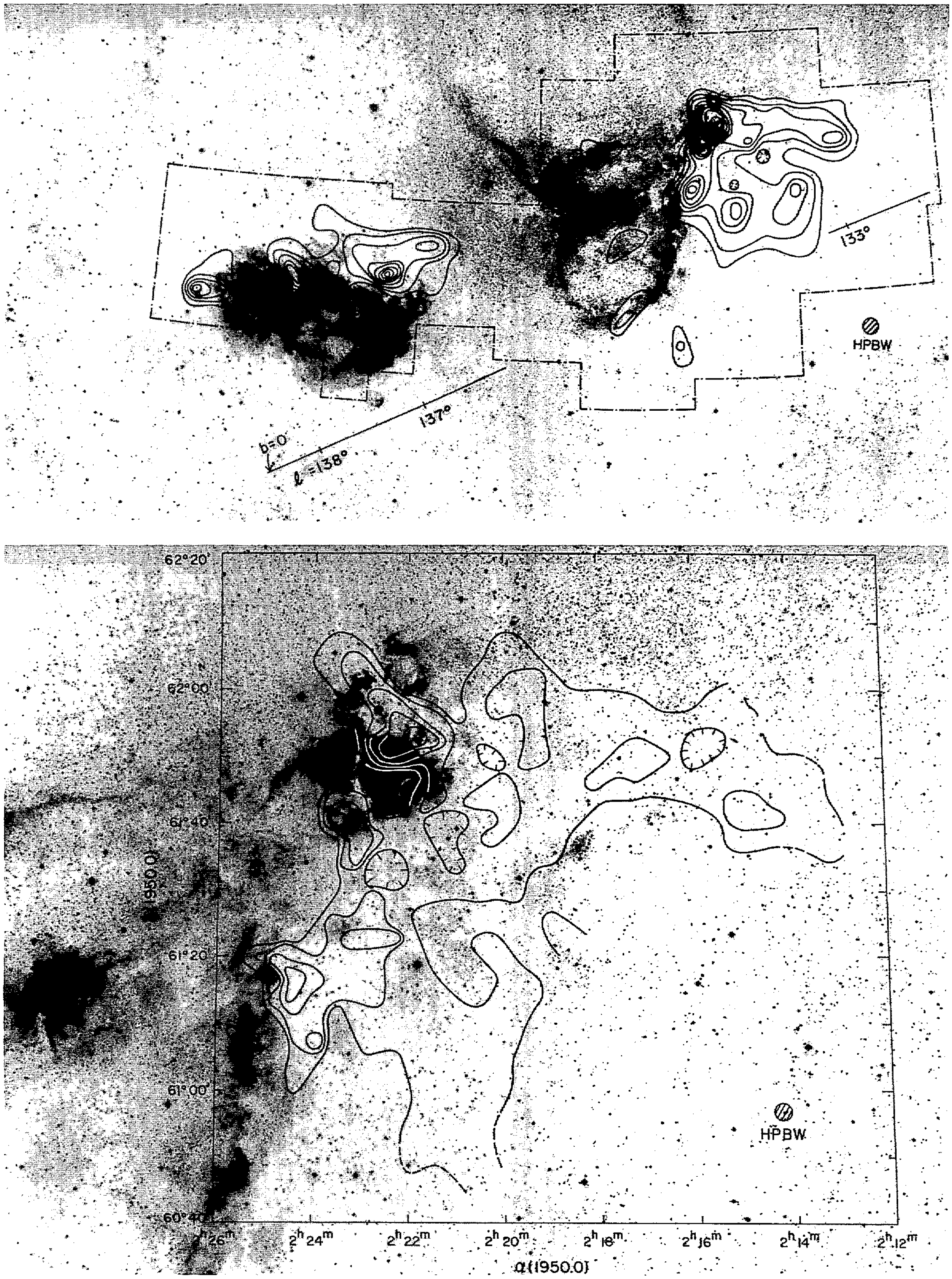

FIG. 1.—(*a*) Map of integrated ^{12}CO emission from the W3–W4–W5 region obtained with the Columbia 1.2 m telescope and superposed on the corresponding red Palomar Sky Survey prints. The contour intervals are in units of 1.5 K MHz. CO emission was completely sampled at full beam spacing within the dashed-dotted lines surrounding the emission regions. W5 is the emission nebula at the left hand of the field ($l \sim 137.5°$), W4 is the large ringlike feature in the center ($l \sim 135°$), while IC 1795 is located at the upper right-hand edge of W4 near the peak of CO emission ($l \sim 134°$). (*b*) Map of ^{12}CO peak brightness temperature (K) from the neighborhood of W4 made with the Texas 5 m telescope and superposed on the corresponding red Sky Survey print. Contour intervals increase in 5 K steps. The CO emission peak near $\delta = 61°50'$ is coincident with the radio source W3, while the CO peak near $\delta = 61°40'$ is near the position of W3(OH).

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